

# The state of a detonating explosive and the velocity of the ejected gases

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With 4 figures in the text

## Introduction

The explosion gases of a detonating high explosive expand with great velocity and compress the air in front of them to a compression layer. The front velocity of the explosion gases ( $v$ ) decreases rapidly towards zero. The compressed air layer expands and gives rise to a shock wave, the front velocity of which ( $w$ ) decreases towards the normal velocity of sound. An important point is the determination of the initial velocity at the surface of the explosive. Accurate measurements of the travelling time as a function of the distance of the front of the compressed air layer from the surface of the explosive have been carried out by WEIBULL (1). The investigation was made with spherical charges of pressed TNT and measuring points were obtained very close to the charge. Nevertheless, it is impossible to determine the initial velocity by means of extrapolation to the surface of the explosive. This is evident from Fig. 1, which shows the front velocity calculated from WEIBULL's values as a function of the reduced radius,  $r = R/Q^{1/3}$ .  $R$  is the distance to the center of the charge in meters, and  $Q$  is the weight of the charge in kilogrammes. The rapid decrease of  $w$  as a function of  $r$  is due to the spherical spread and the resistance of the air.

In order to investigate this question experiments have been made with charges in glass tubes and different air pressures.

## Experimental arrangements

The velocity of the detonation and of the front of the light-emitting gases were determined with a camera with rotating mirror. The charge was reproduced on the film with a speed of about 900 m/s and reduced so that a slope of  $45^\circ$  on the film corresponded to 9000 m/s. The explosive was composed of 40 % TNT and 60 % PETN and was cast in the same glass tubes which were used in determining the velocity. The glass tubes were surrounded by black paper with longitudinal slits, 2 mm wide. Before the measurements the glass tubes were evacuated to the desired pressure.

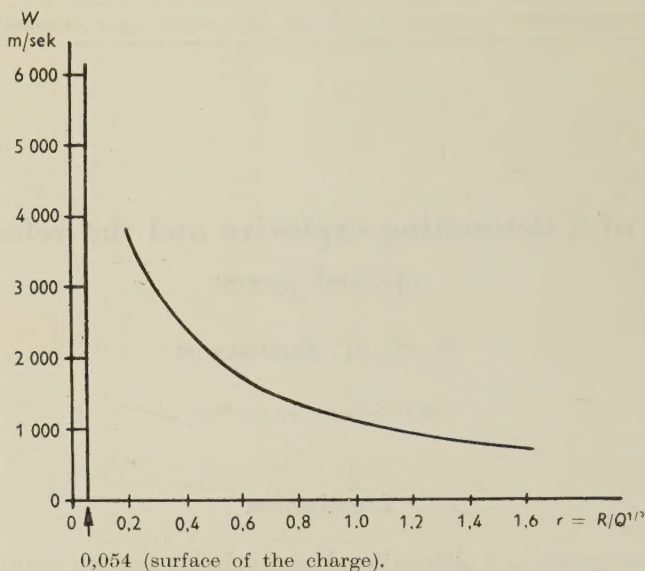


Fig. 1. Frontvelocity of the shock wave from detonating TNT spheres according to measurements of Weibull.

### Experimental results

Figs 2 a–2 c show photographs taken at three different pressures, and Fig. 3 the calculated velocity as a function of the distance from the surface of the explosive. The spread of detonation is approximately the same at all pressures (mean value 7400 m/s), while the front velocity of the light-emitting gases is considerably increased when the air pressure is decreased. At 0.5 mm Hg the mean value of the velocity between 2 and 10 cm, is about 17 500 m/s. At 5 mm Hg it diminishes from about 15 000 m/s near the surface to 9500 m/s at a distance of 10 cm. At atmospheric pressure the velocity is 6500 m/s at 2 cm, and 5000 m/s at 10 cm.

### Previous observations

Similar high velocities in vacuum have earlier been observed by several investigators. The results have, however, been rather overlooked, probably because no satisfactory explanation of the origine and nature of the high velocities was given.<sup>1</sup> BECKER (2) assumed that it is caused by a shock wave, but he did not discuss the question further. In Jahresbericht 1927 of the Chemisch-Technische Reichsanstalt in Berlin (3) is briefly stated that the high velocity cannot be caused by the gases which are flowing behind the detonating wave, but that it, nevertheless, must be caused by gases from the explosive. FRIEDERICH (4) thinks that the observed high velocity is caused by some rapid molecules according to the Maxwellian distribution, an explanation which was disapproved by SCHMIDT (5).

<sup>1</sup> The author is indebted to Mr. S. Ek, who pointed out the existence of earlier observations of high velocities, while discussing the results of this investigation.

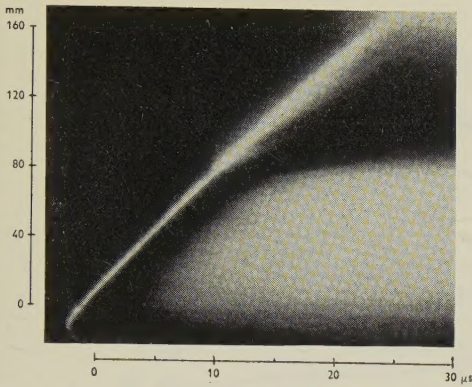


Fig. 2 a. Air pressure 754 mm Hg.

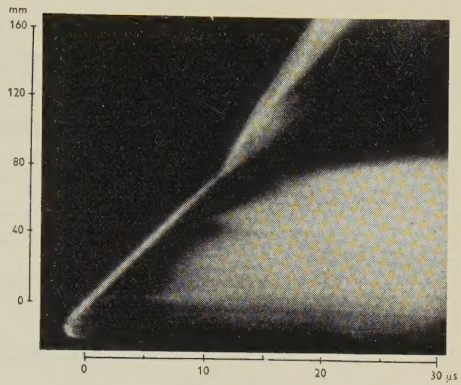


Fig. 2 b. Air pressure 5 mm Hg.

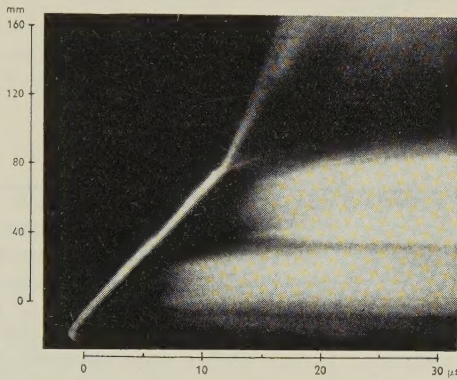


Fig. 2 c. Air pressure 0.5 mm Hg.

### Theoretical explanation of the observed phenomena

As the initial velocity can be assumed to be independent of the air pressure, it must be assumed that the velocity at all pressures decreases from about 20 000 m/s. It is remarkable that the explosion gases are retarded in this way by atmospheric air, the density of which is only about 1/1000 of that of the gases. The observed occurrence can, however, be explained by the existence of a thin layer at the detonating front in which the velocity component forwards is much greater than in the main part of the explosion gases behind the front, as is shown in the schematic diagram in Fig. 4. When the detonation front reaches the end surface, the molecules from the frontal layer go out with their high velocity, but their total mass is so small that even air of atmospheric pressure is sufficient to retard them at a very short distance. Then the front velocity is determined by the lower mean velocity of the following gases. If, on the other hand, the glass tube is evacuated, the reach of the molecules with the high velocity is rather long. Thus, two borderline cases can be distinguished. At very low air pressures, the curves in a diagram of the front velocity as a function of the distance from the surface emanate from a point on the ordinate axis, corresponding to  $\bar{v}_h$  (Fig. 4), and at high pressures they seem to emanate from a point corresponding to  $\bar{v}_l$ .

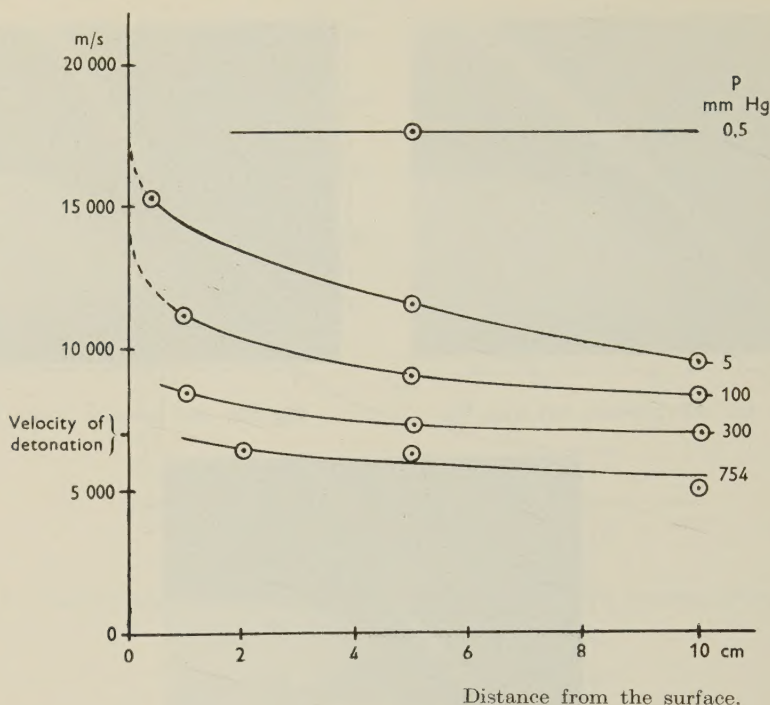


Fig. 3. Frontvelocity of the explosion gases at different air pressure.

There are two important questions in regard to the assumption of a thin frontal layer with high mean velocity. Is this assumption consistent with the well established hydrodynamic theory of detonation, and how can the formation of the frontal layer be explained? The answer to the first question is, that the equations of the hydrodynamic theory are not influenced by a thin frontal layer between the intact explosive and the final state. With regard to the second question it may be necessary to complete the hydrodynamic theory with molecular kinetic considerations. In this rather preliminary paper only a simple linear model, which gives some illustration of the phenomenon, will be discussed.

Particles composed of two parts, each with a mass  $m$ , are assumed to be uniformly distributed on a straight line, with a reflecting barrier at the left end of the row. The particles are further assumed to decompose when initiated by elastic impact, so that one part goes to the left and the other to the right, each with a velocity  $v_0$ . If the particle farthest to the left end is initiated in some way, its right part initiates the nearest neighbour through impact, the right part of which initiates the next neighbour, and so on. The velocities of the particles participating in an impact approach limit values, so that the impacting mass goes to the right with a velocity  $3v_0$ . After the impact it returns with a velocity  $v_0$ , and the two parts of the impacted particle go to the right with a velocity  $v_0$  and  $3v_0$ , respectively. As the decomposition goes on to the right, it is only the front particle which has the velocity  $3v_0$ , and all the others go to and fro impacting each other with the velocity  $v_0$ . When the front reaches the end of the row, only the first particle leaves with the high velocity  $3v_0$ , while all the others have the velocity  $v_0$ .

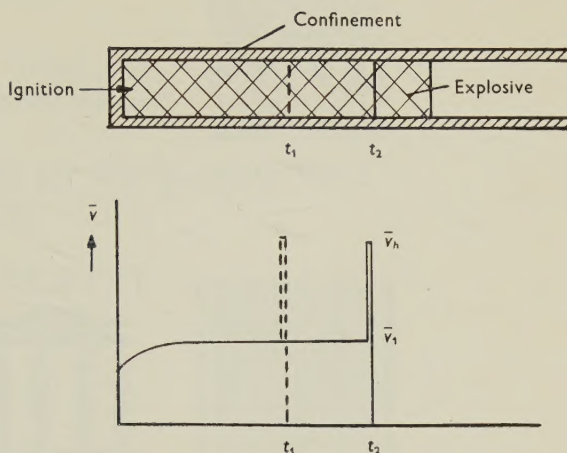


Fig. 4. Schematic diagram of the mean molecule velocity perpendicular to the detonation front ( $v$ ) at two successive times ( $t_1$  and  $t_2$ ).

### Final remarks

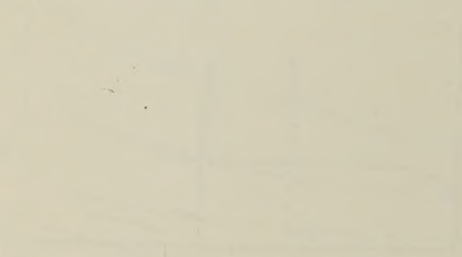
If the assumption of a high-speed layer at the detonating front turns out to be correct on more thorough investigation, this will prove to be important in many ways. The adiabatic compression of the air through a gas front with the initial velocity of 20 000 m/s will, as the author has shown (6), dissociate the air completely, and probably ionise it to a very high degree. This may be of great importance to the igniting capacity and light-emitting power of the explosive. Another consequence of the great speed is that the density of the compressed air has a maximum when the front velocity of the explosion is about 7000 m/s (6), which may explain the occurrence of the second maximum in the pressure of the shock wave, which some explosives show.

LITERATURE. 1. **W. Weibull**, Detonation av klotformiga laddningar i luft: gångtid, front-hastighet och våglängd hos den utsända stötvågen. *Tidskr. f. kustartilleriet* 5 (1947), s. 44—62. — 2. **R. Becker**, Physikalisches über feste und gasförmige Sprengstoffe. *ZS. techn. Physik* 3 (1922), S. 255. — 3. Versuche zur Ermittlung der »Schwadengeschwindigkeit« von Sprengstoffen (Selle). *Jahresbericht Chem. Techn. Reichsanstalt Berlin*, 6 (1927), S. 95—97. — 4. **W. Friederich**, Über die Detonation der Sprengstoffe. *ZS. Ges. Schiess- und Sprengstoffwes.* 28 (1933), S. 114. — 5. **A. Schmidt**, Über die Detonation der Sprengstoffe. *ZS. Ges. Schiess- und Sprengstoffwes.* 28 (1933), S. 243—244, 247. — 6. **C. H. Johansson**, Shock Waves in Gases at the Detonation of brisant Explosives. *Ark. f. mat., astr. o. fysik* 33 A (1946), p. 1—23.

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The following table shows the results of the experiments conducted on the 10th of the month. The data indicates a significant decrease in the rate of reaction as the concentration of the reactants was varied. The results are consistent with the theoretical predictions of the reaction mechanism.

The first series of experiments was conducted at a constant temperature of 25°C. The rate of reaction was measured by the volume of gas evolved over a period of 10 minutes. The results are shown in the table below:

| Concentration of Reactants | Rate of Reaction (ml/min) |
|----------------------------|---------------------------|
| 0.1 M                      | 1.2                       |
| 0.2 M                      | 2.4                       |
| 0.3 M                      | 3.6                       |
| 0.4 M                      | 4.8                       |
| 0.5 M                      | 6.0                       |

The second series of experiments was conducted at a constant concentration of 0.5 M. The rate of reaction was measured by the volume of gas evolved over a period of 10 minutes. The results are shown in the table below:

| Temperature (°C) | Rate of Reaction (ml/min) |
|------------------|---------------------------|
| 15               | 1.0                       |
| 25               | 2.0                       |
| 35               | 3.0                       |
| 45               | 4.0                       |
| 55               | 5.0                       |

The results of these experiments show that the rate of reaction is directly proportional to the concentration of the reactants and the temperature. This is in agreement with the theoretical predictions of the reaction mechanism.